Selected Paper

Development of Radical Reactions with Zirconocene Complexes as Electron Transfer Reagents

Kazuya Fujita, Hideki Yorimitsu, and Koichiro Oshima*

Department of Material Chemistry, Graduate School of Engineering, Kyoto University, Kyoto-daigaku Katsura, Nishikyo-ku, Kyoto 615-8510

Received March 18, 2004; E-mail: oshima@orgrxn.mbox.media.kyoto-u.ac.jp

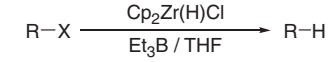
Bis(cyclopentadienyl)zirconium chloride hydride (Schwartz reagent) proved to be an efficient radical chain carrier for radical reduction of organic halides. Treatment of 1-bromoadamantane with $Cp_2Zr(H)Cl$ in THF at 25 °C in the presence of triethylborane furnished adamantane quantitatively. Radical cyclization of 2-haloalkyl allyl ethers afforded five-membered products under the same reaction conditions. Reduction with $Cp_2Zr(H)Cl$ generated in situ from Cp_2ZrCl_2 and sodium bis(2-methoxyethoxy)aluminium hydride (Red-Al) also proceeded smoothly. Moreover, the reduction could function by using a catalytic amount of Cp_2ZrCl_2. A zirconocene–olefin complex also induced reductive radical cyclization of 2-haloalkyl allyl ethers in THF. This complex served as a single electron transfer reagent to promote the radical cyclization. Furthermore, the cyclization reaction in DME afforded 3-tetrahydrofuranylmethylzirconium efficiently.

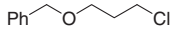
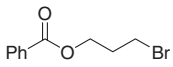
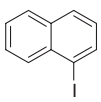
Replacement of halogen atom by hydrogen is of considerable importance in organic synthesis. Dehalogenation reaction can be carried out effectively by a radical process. Radical reaction allows conversion of sensitive polyfunctional compounds, compared with more drastic ionic reaction. Radical reactions are also less susceptible to steric retardation. The majority of radical reactions are based on tin hydrides as reducing agents and chain carriers, mainly on tributyltin hydride.[1,2] However, organotin compounds are toxic and difficult to remove completely from the desired reaction products. Therefore, various attempts have been made to overcome these problems.[3] Silanes[4] and germanes,[5] group 14 metal hydrides, are good alternatives to tributyltin hydride and are used in organic synthesis. The phosphorus–hydrogen bonds in phosphites, phosphines, and hypophosphorous acid are also weak, which allows these reagents to act as hydrogen atom transfer agents and radical chain carriers.[6] However, the reactivity of these alternatives toward organic halides proved to be inferior to that of tributyltin hydride.[7] We found that commercially available $Cp_2Zr(H)Cl$ can be used efficiently instead of tributyltin hydride, where zirconium-centered radical $Cp_2Zr^{III}Cl$ played a key role. Futhermore, we developed a radical cyclization reaction with a zirconocene–olefin complex, which is derived from Cp_2ZrCl_2 and *n*-BuLi.[8,9] Here we describe the radical reduction of various alkyl halides utilizing a single electron transfer from low-valent zirconocene complexes.

Triethylborane-Induced Radical Reaction with Schwartz Reagent[10]

We studied the triethylborane-induced[11] radical reduction of several organic halides with $Cp_2Zr(H)Cl$. Triethylborane (1.0 M hexane solution, 1.0 mmol) as a radical initiator was added to a solution of 1-bromoadamantane (1.0 mmol) and Schwartz reagent (1.5 mmol) in THF (5.0 mL) at room temperature. Concentration followed by silica gel column purification afforded adamantane quantitatively. Table 1 summarizes the results. Most of the reduction reactions of alkyl iodides and bromides proceeded in satisfactory yields. It is noteworthy that reduction of alkyl chlorides, usually unreactive for reduction reaction, with $Cp_2Zr(H)Cl$ completed smoothly in the presence of triethylborane. The primary and secondary alkyl halides as well as tertiary ones were easily reduced to the corresponding hydrocarbons in excellent yields. Reduction of aryl iodide was also very efficient. Functional groups such as ether and ester could survive under the reaction conditions.

Table 1. Stoichiometric Reduction of Organic Halides with Schwartz Reagent[a)]



Entry	R–X	Time/h	Yield/%
1	1-Bromoadamantane	3	94
2	1-Chloroadamantane	5	92
3	n-$C_{10}H_{21}CH(I)CH_3$	3	95
4	n-$C_{10}H_{21}CH(Cl)CH_3$	5	99
5	n-$C_{12}H_{25}Br$	3	98
6		5	82
7		3	90
8		5	89

a) R–X (1.0 mmol), $Cp_2Zr(H)Cl$ (1.5 mmol), Et_3B (1.0 mmol), and THF (5 mL) were employed.

We next focused on radical cyclization[12] of halo acetal and chose halo acetals **1a** and **1b** as model substrates. Treatment of **1a** (0.5 mmol) with $Cp_2Zr(H)Cl$ (1.5 mmol) in the presence of Et_3B (0.5 mmol)[13] in THF (5 mL) at 25 °C for 3 h provided the

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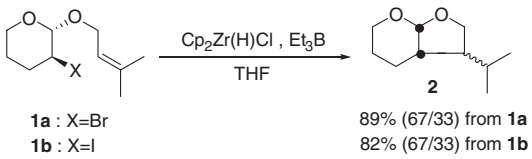
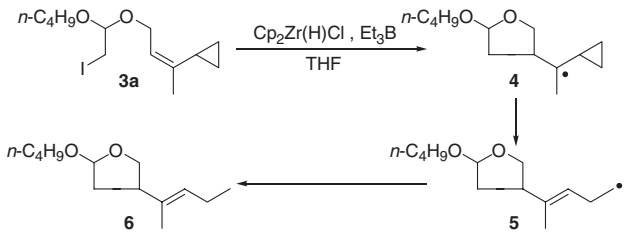
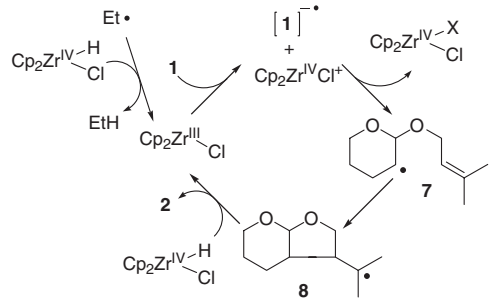


Scheme 1.



Scheme 2.



Scheme 3.

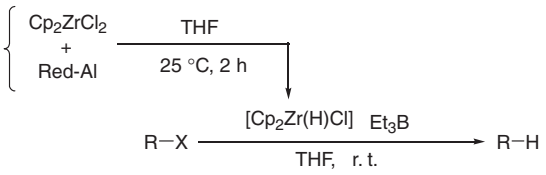
cyclized product **2** in 89% yield (Scheme 1). Treatment of iodo acetal **1b** also afforded **2** in 82% yield.

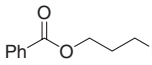
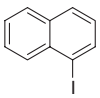
Interestingly, the stereochemical outcome of **2** was quite similar to that in a previous report of radical reactions mediated by *n*-Bu_3SnH.[14] Therefore, the structure of the transition state of radical cyclization would be the same in these reactions. In addition, the reaction of iodo acetal **3a** bearing a cyclopropyl ring provided ring-opening product **6** in 67% yield (Scheme 2). Rapid ring opening of cyclopropyl methyl radical is well known.[15] It is suggested that alkyl radical **4** is generated from **3a**. To our surprise, the double bond has exclusively E stereochemistry.

A plausible reaction mechanism is shown in Scheme 3 in analogy with the case of *n*-Bu_3SnH. An ethyl radical, generated from Et_3B by the action of a trace amount of oxygen,[16] would abstract hydrogen homolytically from $Cp_2Zr(H)Cl$ to provide a zirconium(III) radical species (Cp_2ZrCl). Single electron transfer from Cp_2ZrCl to **1** furnishes the radical anion of **1**. A halide ion is immediately liberated as Cp_2ZrClX (X = Br or I) and the resulting carbon-centered radical **7** cyclizes to afford **8**. The radical **8** would abstract hydrogen from $Cp_2Zr(H)Cl$ to provide the product **2** and regenerate Cp_2ZrCl.

The reaction in Scheme 1 did not complete without Et_3B at ambient temperature. After the mixture was stirred for 3 h, **2** was obtained in 24% yield and **1a** was recovered (68%). Moreover, no product was obtained in the presence of a radical scavenger, 2,2,6,6-tetramethylpiperidine *N*-oxyl. These observations support the radical mechanism in Scheme 3. However,

Table 2. Reduction of Organic Halides with $Cp_2Zr(H)Cl$ Generated in Situ[a)]



Entry	R–X	Time/h	Yield/%
1	1-Bromoadamantane	3	89
2	1-Chloroadamantane	5	88
3	*n*-$C_{10}H_{21}CH(Br)CH_3$	3	94
4	*n*-$C_{10}H_{21}CH(I)CH_3$	3	99
5	*n*-$C_{12}H_{25}Br$	3	93
6	*n*-$C_{12}H_{25}Cl$	15	73
7		3	99
8		5	93

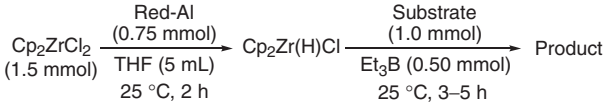
a) R–X (1.0 mmol), Cp_2ZrCl_2 (1.5 mmol), Red-Al (0.75 mmol), Et_3B (1.0 mmol), and THF (5 mL) were employed. b) Cp_2ZrCl_2 (2.5 mmol) and Red-Al (1.25 mmol) were used.

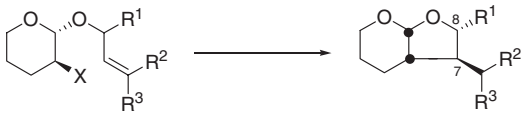
the reaction took place in the absence of any radical initiators in refluxing THF. Single electron transfer from a certain zirconocene complex to an organic halide may induce the spontaneous initiation of the radical reaction. It is also notable that β-alkoxy elimination did not take place in the $Cp_2Zr(H)Cl$-mediated reaction. 3-Methyl-2-buten-1-ol or 9-methyl-6-oxa-4,8-decadien-1-ol was not detected in the reaction mixture. Therefore, a mechanism involving bromine–zirconium exchange followed by intramolecular carbozirconation would be improbable.[17]

Schwartz reagent is not cheap. Next, we investigated the preparation of $Cp_2Zr(H)Cl$ from Cp_2ZrCl_2 and several reducing reagents. As a result, Red-Al [$NaAlH_2(OCH_2CH_2OCH_3)_2$] was found to be most effective.[18] Namely, treatment of Cp_2ZrCl_2 (1.5 mmol) with Red-Al (2.0 M toluene solution, 0.75 mmol) in THF at 25 °C provided Schwartz reagent. Sequential addition of 1-chloroadamantane (1.0 mmol) and Et_3B (1.0 mmol) to the solution afforded adamantane in 88% yield. Various halides were examined, and the results are summarized in Table 2. Not only iodo alkanes but also bromo and chloro alkanes such as 2-bromododecane and 1-chloroadamantane were reduced to the corresponding hydrocarbons in good yields.

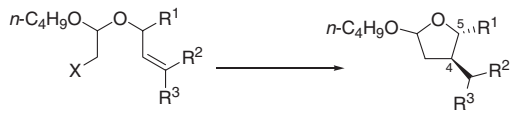
Radical cyclization reaction also took place (Table 3). All halo acetals examined were converted into the corresponding cyclization products in good to excellent yields. The stereochemistry of the products is again highly suggestive of the 3-oxa-5-hexenyl radical intermediates.[14,19] It is worth noting that $Cp_2Zr(H)Cl$ is a hydrogen donor comparable with *n*-Bu_3SnH. Less reactive benzylic radical resulting from the cyclization of **3b** can abstract hydrogen from $Cp_2Zr(H)Cl$ to afford **11**. Although the allylic ether of *o*-iodophenol **14a** was a suitable substrate to construct a dihydrobenzofuran skeleton, a bromo analog of **14a** did not afford the cyclized product un-

Table 3. Radical Cyclization Reaction Using Schwartz Reagent Generated in Situ

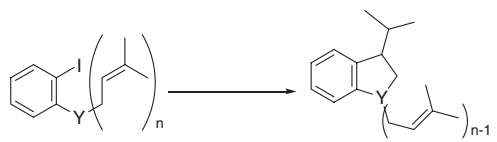




Substrate	X	R^1	R^2	R^3	Product	Yield[a)]
1a	Br	H	Me	Me	**2**	92% (69/31)
1b	I	H	Me	Me	**2**	89% (66/34)
1c	Br	*n*-C_5H_{11}	H	H	**9**	75% (52/48)[b)]
1c	Br	*n*-C_5H_{11}	H	H	**9**	72% (54/46)[b,c)]
1d	I	*n*-C_5H_{11}	H	H	**9**	82% (56/44)[b)]
1d	I	*n*-C_5H_{11}	H	H	**9**	88% (59/41)[b,c)]
1e	I	H	H	*n*-C_3H_7	**10**	87% (83/17)
1e	I	H	H	*n*-C_3H_7	**10**	92% (79/21)[c)]



Substrate	X	R^1	R^2	R^3	Product	Yield[a)]
3b	I	H	H	Ph	**11**	70% (55/45)
3c	Br	H	Me	Me	**12**	90% (66/34)
3d	I	H	Me	Me	**12**	86% (67/33)
3e	Cl	H	Me	Me	**12**	46% (59/41)[d)]
3f	Br	*n*-C_5H_{11}	H	H	**13**	94% (53/47)[e)]
3f	Br	*n*-C_5H_{11}	H	H	**13**	74% (53/47)[c,e)]
3g	I	*n*-C_5H_{11}	H	H	**13**	90% (51/49)[e)]

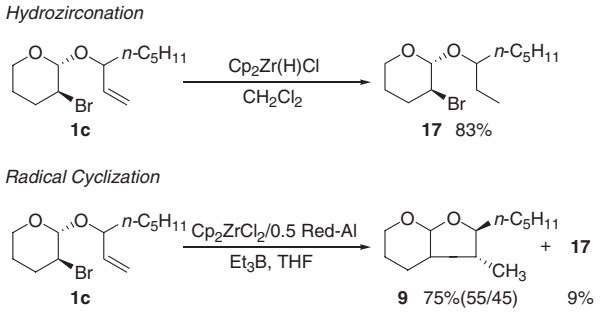


Substrate	Y	*n*	Product	Yield
14a	O	1	**15**	67%
14b	N	2	**16**	68%

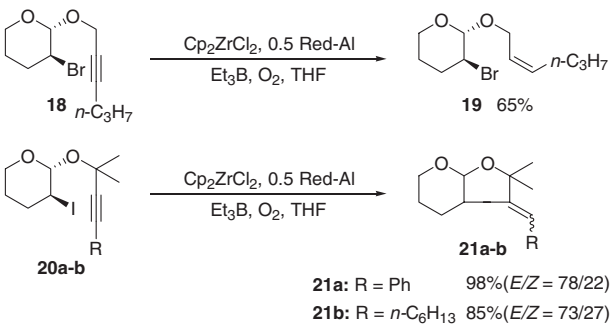
a) Diastereomer ratios are in parentheses. All diastereomers were *cis*-fused. b)The products have 7,8-*trans* configuration. c) The reaction was carried out in refluxing THF in the absence of Et_3B. d) In refluxing THF for 15 h. **3e** (12%) was recovered. e) The products have 4,5-*trans* configuration.

der the same conditions (<5% yield). *o*-Bromophenol and the starting material were obtained in 60% and 35% yields, respectively.[20]

Surprisingly, the reaction proceeded in the absence of Et_3B at higher temperature (Table 3). For example, in refluxing THF, **1e** was treated with $Cp_2Zr(H)Cl$ generated in situ to yield **10** in 92% yield. Although the Zr(II) species is known to undergo single electron transfer to alkyl halide (vide infra), the Et_3B-free system ruled out the possibility of the existence of Zr(II) species that might be generated from transmetallation of ethyl group to Zr(IV) species giving zirconocene ethyl hydride, which then undergoes reductive elimination.



Scheme 4.

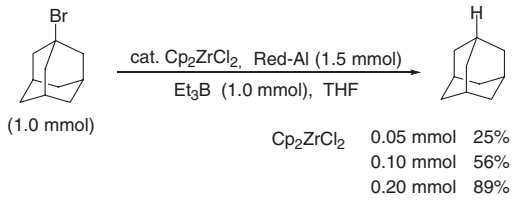


Scheme 5.

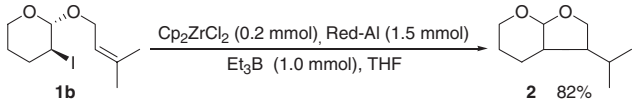
In each case in Table 3, the overall process, that is, a set of single electron transfer, elimination of halogen, radical cyclization, and hydride donation, was preferred to the hydrozirconation reaction[21] under the above reaction conditions. The reaction of the substrate bearing an internal double bond proceeded without contamination by products derived from the hydrozirconation. On the other hand, treatment of **1c** that has a terminal alkene moiety with $Cp_2Zr(H)Cl$ generated in situ in the presence of Et_3B in THF afforded the anticipated bicyclic acetal **9** in 75% yield along with the hydrozirconation product **17** (9%). More interestingly, we have found that the reaction path heavily depends on the reaction conditions (Scheme 4). Treatment of **1c** with three equimolar amounts of purchased $Cp_2Zr(H)Cl$ gave **17** in the absence of Et_3B in CH_2Cl_2 in 83% yield with no trace of **9**. We have succeeded in gaining remarkable control of radical cyclization and hydrozirconation by changing the reaction solvent.

Next, radical cyclization to carbon–carbon triple bond was examined. When halo acetal **18** bearing an acetylenic moiety was used, the major product was **19**, generated by hydrozirconation of the alkyne (Scheme 5).[21] With substituents at the propargyl position, however, the corresponding radical cyclization product **21** was formed exclusively.

Cp_2ZrCl_2 is also not cheap. It is important to reduce the amount of Cp_2ZrCl_2 employed for the reaction. Consequently, we were delighted to discover that the reaction could function with a catalytic amount of Cp_2ZrCl_2. The reduction was performed by addition of Et_3B (1.0 mmol) to a solution of 1-bromoadamantane (1.0 mmol), Cp_2ZrCl_2 (0.2 mmol), and Red-Al (1.5 mmol) in THF. The mixture was stirred for an additional 3 h at ambient temperature to yield adamantane in 89% yield. The reduction reaction did not finish when a smaller amount of Cp_2ZrCl_2 was used. For instance, treatment of 1-bromoada-



Scheme 6.



Scheme 7.

Table 4. Radical Reaction Using a Catalytic Amount of Cp_2ZrCl_2[a)]

Substrate	Product	Yield (Diastereomer ratio)
1a	**2**	80% (61/39)[b)]
1b	**2**	82% (66/34)
1d	**9**	96% (53/47)
3c	**12**	82% (64/36)[b)]
3d	**12**	80% (65/35)
3f	**13**	77% (56/44)[b)]
3g	**13**	96% (53/47)
14b	**16**	83%

a) The reactions were performed at room temperature in THF for 3–5 h unless otherwise noted. Cp_2ZrCl_2 (0.2 eq.), Red-Al (1.5 eq.), and Et_3B (1.0 eq.) were employed. b) In refluxing THF for 5 h. Cp_2ZrCl_2 (0.3 eq.) was used.

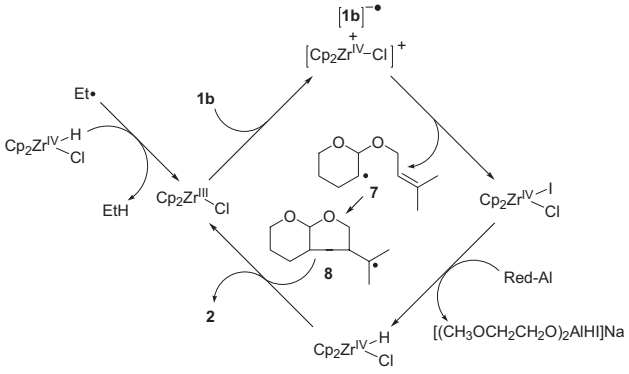
mantane with Red-Al and Et_3B in the presence of Cp_2ZrCl_2 (5 mol%) provided adamantane in only 25% yield and 71% of 1-bromoadamantane remained unchanged (Scheme 6).

The zirconium hydride-induced radical cyclization reaction also proceeded effectively in a catalytic manner. Treatment of iodo acetal **1b** with Cp_2ZrCl_2 in THF in the presence of Red-Al and Et_3B at room temperature afforded **2** in 82% yield (Scheme 7). Table 4 summarizes the results. Not only iodo acetal but also bromo acetal and a 2-iodoaniline derivative reacted easily to give the corresponding cyclic products. Bromo acetals were generally less reactive than iodo acetals and the corresponding cyclization products were obtained in lower yields along with the starting materials. Higher temperature was necessary to complete the reduction of bromo acetals.

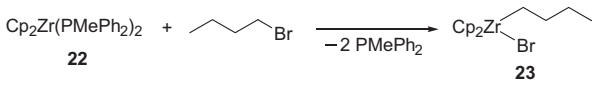
We assumed the catalytic mechanism shown in Scheme 8. Alkyl radical **7**, formed by the electron transfer to iodo acetal from $Cp_2Zr^{III}Cl$ cyclizes to afford the radical **8**. On the other hand, zirconocene chloride iodide would be reduced into $Cp_2Zr(H)Cl$ by the action of Red-Al. The $Cp_2Zr(H)Cl$ works again as a hydrogen source for the carbon-centered radical **8**.

Radical Cyclization with a Zirconocene–Olefin Complex[22]

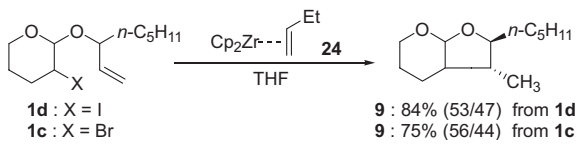
Next, we attempted the radical reaction with Cp_2Zr^{II} species. There are a few reports about dehalogenation reaction of organic halides with $Cp_2Zr(H_2C{=}CHEt)$. Initially, Schwartz's group investigated the oxidation of Cp_2ZrL_2 **22**



Scheme 8.



Scheme 9.



Scheme 10.

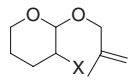
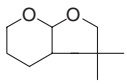
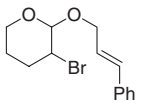
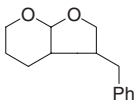
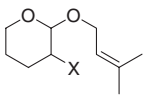
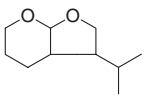
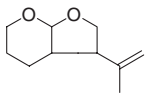
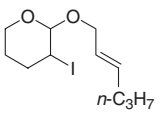
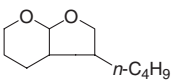
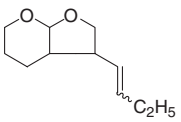
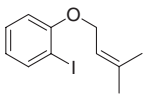
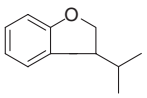
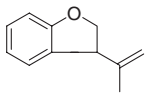
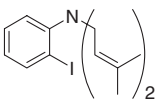
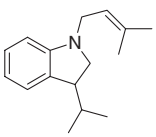
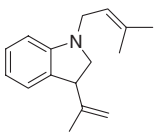
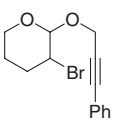
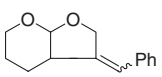
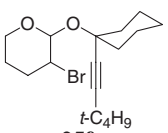
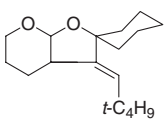
(L = $PMePh_2$ or PMe_2Ph) by alkyl halide and found that a formal oxidative addition product **23** was formed (Scheme 9).[23] A mechanism involving intermediary organic radicals generated by single electron transfer from zirconocene–olefin complex $Cp_2Zr(H_2C{=}CHEt)$ to alkyl halide has been established. However, their interest was directed toward the systematic investigation of the oxidation process in the reaction, and the synthetic utility of this single electron transfer from $Cp_2Zr(H_2C{=}CHEt)$ remains largely unknown. Thus, we examined to utilize $Cp_2Zr(H_2C{=}CHEt)$ as a single electron transfer reagent in radical reaction.

The radical cyclization of various halo acetals with $Cp_2Zr(H_2C{=}CHEt)$ was examined. Treatment of Cp_2ZrCl_2 (2.0 mmol) with *n*-BuLi (1.5 M in hexane, 4.0 mmol) in THF (10 mL) at −78 °C provided $Cp_2Zr(H_2C{=}CHEt)$ (**24**). After stirring for 30 min at the same temperature, a THF solution of iodo acetal **1d** was added, and the mixture was warmed to 25 °C over 2 h. After being stirred for another 1 h at 25 °C, the reaction mixture was poured into 1 M HCl (30 mL). Silica gel column purification afforded the corresponding cyclization product **9** in 84% yield (Scheme 10). The product was obtained with high *trans* selectivity with respect to the pentyl and methyl groups. Bromo acetal **1c** also underwent cyclization upon treatment with the zirconocene complex.

Table 5 summarizes the results. Several comments are worth noting.

(1) Not only iodo and bromo acetals but also less reactive chloro acetals were found to be effective for the $Cp_2Zr(H_2C{=}CHEt)$-based cyclization reaction. This method would thus extend the scope of substrates in radical cyclization reaction (Entries 1 and 3).

Table 5. Radical Cyclization Reaction with Zirconocene–Olefin Complex[a)]

Entry	Substrate	Product[b)]	
1	 **25a**: X = Br **25b**: X = Cl	 **26**: 72% **26**: 34%	
2	 **25c**	 **27**: 73% (57/43)	
3	 **1b**: X = I **1a**: X = Br **25d**: X = Cl	 **2**: 49% (67/33) **2**: 48% (68/32) **2**: 44% (70/30)	 **28**: 45% (68/32) **28**: 48% (69/31) **28**: 53% (67/33)
4	 **1e**	 **10**: 46% (86/14)	 **29**: 19% (82/18)
5	 **14a**	 **15**: 54%	 **30**: 26%
6	 **14b**	 **16**: 63%	 **31**: 36%
7	 **25e**	 **32**: 67% (*E*/*Z* = 27/73)	
8	 **25f**	 **33**: 80% (*E* only)[c)]	

a) Substrate (1.0 mmol), Cp_2ZrCl_2 (2.0 mmol), *n*-BuLi (4.0 mmol, 1.5 M hexane), and THF (12 mL) were employed. b) Diastereomer ratios are in parentheses. c) Evidenced by NOE study.

(2) Treatment of the substrates with a disubstituted or trisubstituted olefinic moiety as a radical acceptor furnished a mixture of alkyl-substituted and alkenyl-substituted tetrahydrofurans (Entries 3–6).

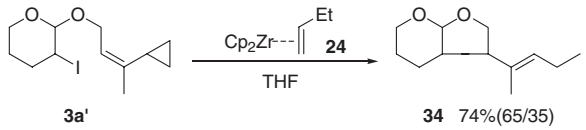
(3) Cyclization of 2-iodophenol derivative **14a** and 2-iodoaniline derivative **14b** could be also achieved efficiently to afford the corresponding dihydrobenzofuran and indoline derivative, respectively (Entries 5 and 6). Bromo analogues of **14a** and **14b** did not provide the cyclized products under the same conditions.

(4) Our cyclization protocol could be successfully applied to halo acetals bearing an acetylenic moiety as a radical acceptor (Entries 7 and 8). The reaction of **25f** provided tetrahydrofuran derivative **33** as a single stereoisomer.

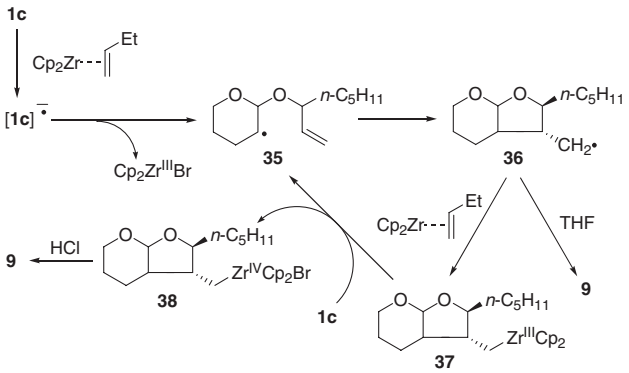
We propose a radical reaction mechanism on the basis of the following results.

(1) The stereochemical outcome illustrated in Table 5 was quite similar to that in the previous report of radical reactions mediated by *n*-Bu_3SnH.

(2) Treatment of iodo acetal **3a′**, possessing a cyclopropane ring on the alkenyl carbon, with zirconocene–olefin complex **24** provided tetrahydrofuran derivative **34** in 74% yield. No trace of products with a cyclopropane ring was found in the crude reaction mixture (Scheme 11).[12]



Scheme 11.

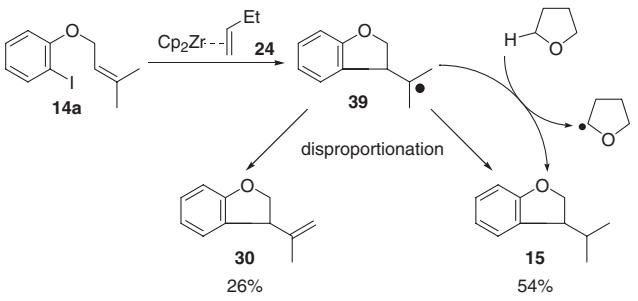


Scheme 12.

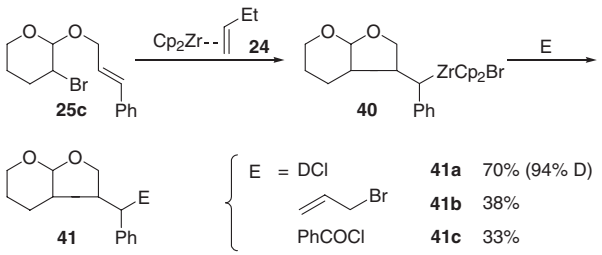
(3) It is also remarkable that β-alkoxy elimination did not proceed in this system. Therefore, a mechanism involving oxidative addition of alkyl halide to zirconocene–olefin complex **24** followed by intramolecular carbozirconation would be improbable.

(4) In addition to these results, no product was obtained in the presence of a radical scavenger such as 2,2,6,6-tetramethylpiperidine *N*-oxyl. The starting material remained unchanged.

Based on these facts and the Schwartz's protocol,[23] we are tempted to assume the reaction mechanism as follows (Scheme 12): A single electron transfer from the zirconocene–olefin complex to **1c** yields the radical anion of **1c**. A halide ion is immediately liberates as $Cp_2ZrBr(III)$. The resulting carbon-centered radical **35** cyclizes to afford **36**. Some of radical **36** would abstract hydrogen from THF[24] to provide the product **9**. Others recombine with the zirconocene–olefin complex, yielding the corresponding alkylzirconium(III) species **37**. Subsequent abstraction of halogen from halo acetal **1c** gives rise to the corresponding zirconium(IV) species **38** along



Scheme 13.



Scheme 14.

with regeneration of alkyl radical **35**. Recombination of the radical **36** with $Cp_2Zr^{III}Br$ to afford **38** might be an alternative pathway.[25] Hydrolysis furnishes the cyclized product **9**. The formation of **38** could be confirmed by quenching the reaction mixture with DCl in place of HCl. However, deuterium was not completely incorporated (54%). Therefore, we can not exclude the path of hydrogen abstraction from THF.

The formation of alkenyl-substituted products can be explained as follows (Scheme 13): 2-Iodophenyl 3-methyl-2-butenyl ether (**14a**) would undergo cyclization to afford an alkyl radical **39**. Some of the radical would abstract hydrogen from the solvent to furnish saturated product **15**. The rest would disproportionate to provide the products **15** and **30**.

Finally, the cyclization reaction was examined in several solvents. In ether, a reductive radical cyclization product was obtained in a yield comparable with the reaction in THF. Surprisingly, the use of DME as a solvent dramatically changed the reaction pathway. In this case, 2,9-dioxabicyclo[4.3.0]nonan-7-ylmethylzirconium **40** was cleanly formed. It is assumed that the alkyl radical species resulting from cyclizaton of **25c** would abstract hydrogen less efficiently from DME than from THF and that most of them recombine with the zirconocene–olefin complex. The existence of **40** was unambiguously verified by deuterolysis to afford **41a** in 70% yield with 94% deuterium incorporation (Scheme 14). The alkylzirconium species **40** could also be trapped by electrophiles such as allyl bromide and benzoyl chloride in the presence of a stoichiometric amount of CuCN.[26,27]

In conclusion, we have found the Schwartz reagent could mediate a radical reduction process as a promising alternative to tributyltin hydride. It rivals tributyltin hydride in efficiency and is superior from an ecological and toxicological perspective. The key steps would be homolytic cleavage of the zirconium–hydrogen bond and halogen reduction by $Cp_2Zr^{III}Cl$. Although these fundamental reactions are well established in the case of hydrosilanes, hydrogermanes, and hydrostannanes, the present results will develop a new and attractive aspect of transition metal–hydrido complexes. Furthermore, we have also demonstrated that the Negishi reagent is valuable for the radical cyclization reaction.[28] Our reaction protocol confirms that the zirconocene–olefin complex is an efficient single electron transfer reagent and develops an alternative aspect of the zirconocene–olefin complex.

Experimental

NMR spectra (^1H and ^{13}C) were recorded on a Varian GEMINI 300 spectrometer in $CDCl_3$; tetramethylsilane (TMS) was used as an internal standard. IR spectra were determined on a JASCO IR-810 spectrometer and a SHIMADZU FTIR-8200PC spectrometer. Mass spectra were determined on a JEOL Mstation 700 spectrometer. TLC analyses were performed on commercial glass plates bearing 0.25 mm layer of Merck Silica-gel $60F_{254}$. Silica gel (Wakogel 200 mesh) was used for column chromatography. The analyses were carried out at the Elemental Analysis Center of Kyoto University. Unless otherwise noted, materials obtained from commercial suppliers were used without further purification. Tetrahydrofuran (THF) was freshly distilled from sodium benzophenone ketyl before use. Dichloromethane was dried with molecular sieves 4A. Hexane and DME were dried over slices of sodium. $Cp_2Zr(H)Cl$ was purchased from Aldrich Chemicals and was used as received. Red-Al® (70 wt% in toluene) was purchased from Nacalai Tesque Inc. and was stored under argon. The use of newly purchased Red-Al is recommended. Et_3B was purchased from Aldrich Chemicals and was diluted to prepare a 1.0 M hexane solution, which was stored strictly under argon. Cp_2ZrCl_2 was purchased from Tokyo Kasei Kogyo and was used as received. As for the reaction with $Cp_2Zr(H)Cl$, all the reactions were performed in a reaction flask equipped with a toy balloon that was filled with argon unless otherwise noted. Oxygen, which is necessary to produce an ethyl radical from triethylborane, could penetrate the balloon easily and the concentration of oxygen in the balloon reaches 10% after 12 h.

Preparation of Starting Materials. The preparation of starting iodo acetals was carried out according to a literature method[29] with corresponding vinyl ethers, allylic alcohols and *N*-iodosuccinimide.

Procedure for Reductive Cyclization by Commercially Available Schwartz Reagent. THF (3 mL) was added to $Cp_2Zr(H)Cl$ (387 mg, 1.5 mmol) in a 50-mL reaction flask under argon. Iodo acetal **1b** (148 mg, 0.50 mmol in 2 mL of THF) and triethylborane (1.0 M hexane solution, 0.50 mL, 0.50 mmol) were added. The heterogeneous reaction mixture turned to a clear yellow solution with stirring for 1 h at 25 °C. After being stirred for an additional 2 h, the mixture was poured into hydrochloric acid (30 mL, 1 M) and stirred for 15 min. The resulting products were extracted with hexane/ethyl acetate (10/1, 30 mL × 3). The combined organic layer was dried over Na_2SO_4 and concentrated in vacuo. Silica gel column purification (hexane/ethyl acetate = 20/1) of the crude oil provided **2** (70 mg, 0.41 mmol) in 82% yield.

Typical Procedure Using $Cp_2Zr(H)Cl$ Generated in Situ. Cp_2ZrCl_2 (219 mg, 0.75 mmol) and sodium bis(2-methoxyethoxy)aluminium hydride (Red-Al, 2.0 M toluene solution, 0.38 mL, 0.75 mmol) were mixed in THF (3 mL) under argon and were stirred for 2 h at 25 °C to form the Schwartz reagent. Bromo acetal **1a** (125 mg, 0.50 mmol) in THF (2 mL) and triethylborane (1.0 M hexane solution, 0.50 mL, 0.50 mmol) were successively added. A

clear solution was obtained while stirring for 3 h. The mixture was poured into 1 M HCl and was stirred for 15 min. Extraction with hexane/ethyl acetate (10/1, 30 mL × 3) followed by silica gel column purification afforded **2** (78 mg) in 92% yield.

Radical Reaction Employing a Catalytic Amount of Cp_2ZrCl_2. THF (6 mL) was added to Cp_2ZrCl_2 (59 mg, 0.20 mmol) in a 50-mL reaction flask filled with argon. Red-Al (2.0 M toluene solution, 0.75 mL, 1.5 mmol) was added and the mixture was stirred for 1 h. Then, **1d** (354 mg, 1.0 mmol) in THF (4 mL) and triethylborane in hexane (1.0 M, 1.0 mL, 1.0 mmol) were added. The resulting mixture was stirred for 3 h. Quenching the reaction with hydrochloric acid, followed by extraction, concentration, and silica gel column purification yielded 220 mg of **9** (0.96 mmol, 96%) as a colorless oil.

Hydrozirconation of 1c in Dichloromethane. Dichloromethane (3 mL) was added to $Cp_2Zr(H)Cl$ (387 mg, 1.5 mmol) kept strictly under argon atmosphere. Bromo acetal **1c** (145 mg, 0.50 mmol in 2 mL of CH_2Cl_2) was then added and the resulting mixture was stirred for 3 h at room temperature. Workup as above provided **17** (122 mg, 0.42 mmol, 83%).

Radical Cyclization Reaction with a Zirconocene–Olefin Complex in THF. Cp_2ZrCl_2 (585 mg, 2.0 mmol) was treated with *n*-BuLi (1.5 M in hexane, 2.7 mL, 4.0 mmol) in THF at −78 °C for 30 min to prepare a zirconocene–olefin complex **24**. A solution of iodo acetal **1d** (297 mg, 1.0 mmol) in THF (2 mL) was added to the reaction mixture at the same temperature. The temperature was then raised to ambient temperature, and the whole mixture was stirred for an additional 3 h. Quenching 1 M HCl (30 mL) and extraction with hexane/ethyl acetate (10/1 = v/v%, 20 mL × 3) followed by silica gel column purification afforded the corresponding cyclization product **9** (179 mg, 0.84 mmol) in 84% yield.

Typical Experimental Procedure for Cyclization Reaction in DME. Cp_2ZrCl_2 (585 mg, 2.0 mmol) and *n*-BuLi (1.5 M in hexane, 2.7 mL, 4.0 mmol) were mixed in DME at 0 °C under argon and were stirred for 1 h at 0 °C to form a zirconocene–olefin complex **24**. A solution of bromo acetal **25c** (297 mg, 1.0 mmol) in DME (2 mL) was added to the reaction mixture at 0 °C. The temperature was then raised to ambient temperature, and the stirring was continued for 3 h to yield alkylzirconium **40**. The mixture was poured into deuterochloric acid (10 mL, 1 M) and stirred for 30 min. The resulting products were extracted with hexane three times. The combined organic layer was dried over Na_2SO_4 and concentrated in vacuo. Silica gel column purification (hexane/ethyl acetate = 10/1) of the crude oil provided **41a** (152 mg, 0.70 mmol) in 70% yield with 94% deuterium incorporation.

Characterization Data. Spectral data for some compounds (**1b–1d**, **2**, **3c**, **3d**, **3f**, **3g**, **9**, **12–15**, **19**, **21**, **25c**, **25d**, **26**, and **28–32**) were found in the literature.[11,14,19] Identification of *E* and *Z* isomers of **21**, **32**, and **33** was carried out by comparing their ^{1}H NMR spectra with known compounds.[6c] Isomeric ratios were determined by fine ^{1}H NMR spectra.

***trans*-3-Bromo-2-(3-methyl-2-butenyloxy)tetrahydropyran (1a).** IR (neat) 2924, 2872, 2852, 1776, 1676, 1442, 1377, 1204, 1130, 1086, 1072, 1021, 946, 869, 727 cm^{-1}; ^{1}H NMR ($CDCl_3$) δ 1.47–1.59 (m, 1H), 1.69 (s, 3H), 1.76 (s, 3H), 1.86–2.00 (m, 2H), 2.34–2.45 (m, 1H), 3.58 (ddd, J = 8.4, 6.3, 5.1 Hz, 1H), 3.88–4.02 (m, 2H), 4.08 (dd, J = 11.7, 6.9, 1H), 4.22 (dd, J = 11.7, 6.6 Hz, 1H), 4.63 (d, J = 5.1 Hz, 1H), 5.36 (dd, J = 6.9, 6.6 Hz, 1H); ^{13}C NMR ($CDCl_3$) δ 17.83, 23.16, 25.67, 29.99, 49.48, 62.36, 64.26, 99.94, 120.11, 138.09. Found: C, 48.28; H, 6.62%. Calcd for $C_{10}H_{17}BrO_2$: C, 48.21; H, 6.88%.

***trans*-3-Iodo-2-(2-hexenyloxy)tetrahydropyran (1e).** IR (neat) 2912, 2846, 1672, 1463, 1436, 1354, 1303, 1202, 1122, 1068, 866, 695 cm^{-1}; ^{1}H NMR ($CDCl_3$) δ 0.89 (t, J = 7.2 Hz, 3H), 1.42 (tq, J = 7.2, 7.2 Hz, 2H), 1.50–1.61 (m, 1H), 1.69–1.80 (m, 1H), 1.94–2.04 (m, 1H), 2.02 (dt, J = 6.6, 7.2 Hz, 2H), 2.31–2.41 (m, 1H), 3.56 (ddd, J = 11.7, 7.8, 3.9 Hz, 1H), 3.93–4.00 (m, 2H), 4.09 (ddd, J = 8.1, 4.5, 4.5 Hz, 1H), 4.18 (dd, J = 11.7, 6.6 Hz, 1H), 4.66 (d, J = 4.5 Hz, 1H), 5.56 (ddd, J = 15.3, 6.6, 6.6 Hz, 1H), 5.71 (ddd, J = 15.3, 6.6, 6.6 Hz, 1H); ^{13}C NMR ($CDCl_3$) δ 13.55, 22.03, 25.40, 29.39, 32.61, 34.24, 63.35, 68.85, 101.27, 125.56, 135.38. Found: C, 42.45; H, 6.04%. Calcd for $C_{11}H_{19}IO_2$: C, 42.60; H, 6.17%.

2-Iodoethanal Butyl 3-Phenyl-2-propenyl Acetal (3b). IR (neat) 3022, 2952, 2928, 2866, 1599, 1495, 1450, 1415, 1378, 1346, 1176, 1112, 1037, 966, 741, 691 cm^{-1}; ^{1}H NMR ($CDCl_3$) δ 0.93 (t, J = 7.2 Hz, 3H), 1.42 (tq, J = 7.2, 7.2 Hz, 2H), 1.42 (ddt, J = 6.6, 6.6, 7.2 Hz, 2H), 3.25 (d, J = 5.7 Hz, 2H), 3.50 (dt, J = 9.3, 6.6 Hz, 1H), 3.62 (dt, J = 9.3, 6.6 Hz, 1H), 4.21 (dd, J = 12.6, 6.3 Hz, 1H), 4.30 (dd, J = 12.6, 6.0 Hz, 1H), 4.70 (t, J = 5.7 Hz, 1H), 6.28 (ddd, J = 15.9, 6.3, 6.0 Hz, 1H), 6.63 (d, J = 15.9 Hz, 1H), 7.20–7.41 (m, 5H); ^{13}C NMR ($CDCl_3$) For major isomer: δ 5.12, 13.62, 19.07, 31.49, 66.07, 66.76, 101.09, 125.26, 126.40, 127.67, 128.47, 132.49, 136.46. Found: C, 50.24; H, 6.11%. Calcd for $C_{15}H_{21}IO_2$: C, 50.01; H, 5.88%.

2-Chloroethanal Butyl 3-Methyl-2-butenyl Acetal (3e). IR (neat) 2958, 2930, 2870, 1671, 1440, 1379, 1254, 1195, 1120, 1040, 763 cm^{-1}; ^{1}H NMR ($CDCl_3$) δ 0.93 (t, J = 7.8 Hz, 3H), 1.41 (tq, J = 6.9, 7.8 Hz, 2H), 1.59 (ddt, J = 6.6, 6.6, 6.9 Hz, 2H), 1.69 (s, 3H), 1.75 (s, 3H), 3.51 (d, J = 5.4, 2H), 3.47–3.57 (m, 1H), 3.58–3.68 (m, 1H), 4.07 (dd, J = 10.4, 7.5 Hz, 1H), 4.15 (dd, J = 10.4, 6.9 Hz, 1H), 4.65 (t, J = 5.4 Hz, 1H), 5.35 (dd, J = 6.9, 7.5 Hz, 1H); ^{13}C NMR ($CDCl_3$) δ 13.46, 17.59, 18.96, 25.39, 31.53, 43.50, 62.95, 66.08, 100.84, 120.27, 137.35. Found: C, 59.55; H, 9.57%. Calcd for $C_{11}H_{21}ClO_2$: C, 59.85; H, 9.59%.

7-Butyl-2,9-dioxabicyclo[4.3.0]nonane (10, Mixture of Diastereomers, 83/17). IR (neat) 2924, 2856, 1724, 1467, 1403, 1253, 1146, 1090, 1023, 949, 902, 870 cm^{-1}; ^{1}H NMR ($CDCl_3$) δ 0.90 (t, J = 6.9 Hz, 3H), 1.10–1.45 (m, 7H), 1.54–1.98 (m, 4H), 2.25–2.37 (m, 1H), 3.42 (ddd, J = 11.4, 11.4, 1.8 Hz, 0.17H), 3.54 (dd, J = 8.4, 8.4 Hz, 0.17H), 3.60–3.69 (m, 1.66H), 3.70–3.80 (m, 0.83H), 3.80–3.94 (m, 0.17H), 3.95 (dd, J = 8.1, 8.1 Hz, 0.83H), 4.28 (dd, J = 8.4, 8.4 Hz, 0.17H), 5.00 (d, J = 3.6 Hz, 0.17H), 5.28 (d, J = 3.6 Hz, 0.83H); ^{13}C NMR ($CDCl_3$) For major isomer: δ 13.83, 19.05, 22.74, 23.12, 26.55, 30.35, 36.41, 40.91, 60.89, 70.12, 102.06. For minor isomer: δ 13.83, 20.61, 22.30, 22.78, 30.62, 32.32, 37.74, 44.06, 64.42, 74.26, 102.06. Found: C, 71.57; H, 11.21%. Calcd for $C_{11}H_{20}O_2$: C, 71.70; H, 10.94%.

2-Butoxy-4-phenylmethyltetrahydrofuran (11, Mixture of Stereoisomers, 55/45). IR (neat) 2928, 2864, 1603, 1492, 1449, 1341, 1174, 1030, 915, 740, 698 cm^{-1}; ^{1}H NMR ($CDCl_3$) δ 0.90 (t, J = 7.2 Hz, 1.65H), 0.94 (t, J = 7.2 Hz, 1.35H), 1.27–1.73 (m, 5H), 1.99 (dd, J = 12.6, 7.2 Hz, 0.55H), 2.17 (ddd, J = 14.4, 9.0, 5.4 Hz, 0.45H), 2.40–2.80 (m, 3H), 3.35 (dt, J = 6.6, 9.9 Hz, 0.45H), 3.38 (dt, J = 6.6, 9.9 Hz, 0.55H), 3.53–3.74 (m, 2H), 3.90 (dd, J = 8.1, 7.2 Hz, 0.45H), 3.97 (dd, J = 8.1, 7.2 Hz, 0.55H), 5.08–5,15 (m, 1H), 7.14–7.31 (m, 5H); ^{13}C NMR ($CDCl_3$) For major isomer: δ 13.70, 19.26, 31.68, 38.55, 38.98, 39.82, 67.00, 71.65, 104.08, 126.14, 128.46, 128.72, 140.64. For minor isomer: δ 13.73, 19.28, 31.77, 38.69, 39.26, 39.89, 67.35, 71.65, 104.53, 126.06, 128.46, 128.67,

140.94. Found: C, 76.81; H, 9.69%. Calcd for $C_{15}H_{22}O_2$: C, 76.88; H, 9.46%.

3-Isopropyl-1-prenylindoline (16). IR (neat) 3042, 3022, 2954, 2922, 2866, 1672, 1605, 1491, 1459, 1384, 1249, 1156, 1023, 923, 843, 741, 723 cm^{-1}; ^1H NMR ($CDCl_3$) δ 0.87 (d, $J =$ 6.9 Hz, 3H), 0.98 (d, $J = 6.9$ Hz, 3H), 1.71 (s, 3H), 1.74 (s, 3H), 1.97–2.09 (m, 1H), 3.03–3.17 (m, 2H), 3.27–3.37 (m, 1H), 3.67 (d, $J = 6.6$ Hz, 2H), 5.27 (t, $J = 6.6$ Hz, 1H), 6.47 (d, $J = 8.1$ Hz, 1H), 6.63 (dd, $J = 7.5$, 7.5 Hz, 1H), 7.04–7.11 (m, 2H); ^{13}C NMR ($CDCl_3$) δ 17.89, 18.62, 20.42, 25.65, 30.60, 46.42, 46.76, 55.02, 107.09, 117.07, 120.35, 124.51, 127.47, 132.80, 135.19, 152.83. Found: C, 83.79; H, 10.11%. Calcd for $C_{16}H_{23}N$: C, 83.68; H, 10.17%.

3-Bromo-2-(1-ethylhexanyloxy)tetrahydropyran (17, Mixture of Diastereomers, 50/50). IR (neat) 2928, 2856, 2726, 1465, 1378, 1354, 1204, 1152, 1126, 1086, 1071, 1022, 946, 914, 870, 726 cm^{-1}; ^1H NMR ($CDCl_3$) δ 0.86–0.96 (m, 6H), 1.23–1.63 (m, 11H), 1.81–2.01 (m, 2H), 2.34–2.46 (m, 1H), 3.51–3.63 (m, 2H), 3.92–4.02 (m, 2H), 4.64 (d, $J = 5.1$ Hz, 1H); ^{13}C NMR ($CDCl_3$) δ 8.81, 9.52, 13.84, 13.84, 22.41, 22.41, 23.76, 23.84, 24.35, 24.90, 25.52, 27.46, 30.77, 30.85, 31.79, 31.86, 32.64, 32.74, 50.21, 50.21, 62.89, 62.95, 79.02, 79.61, 100.09, 100.45. Found: C, 53.17; H, 8.78%. Calcd for $C_{13}H_{25}BrO_2$: C, 53.25; H, 8.59%.

3-Bromo-2-(3-phenyl-2-propenyloxy)tetrahydropyran (25c). IR (neat) 3022, 2944, 2850, 1949, 1726, 1705, 1657, 1600, 1579, 1495, 1449, 1356, 1203, 869, 730, 691 cm^{-1}; ^1H NMR ($CDCl_3$) δ 1.46–1.57 (m, 1H), 1.85–1.99 (m, 2H), 2.34–2.46 (m, 1H), 3.58 (ddd, $J = 3.6$, 6.3, 11.4 Hz, 1H), 3.94 (ddd, $J = 3.6$, 7.8, 11.4 Hz, 1H), 4.02 (ddd, $J = 4.2$, 4.2, 6.6 Hz, 1H), 4.21 (dd, $J = 6.6$, 12.9 Hz, 1H), 4.41 (dd, $J = 5.7$, 12.9 Hz, 1H), 4.70 (d, $J = 4.2$ Hz, 1H), 6.29 (ddd, $J = 5.7$, 6.6, 15.9 Hz, 1H), 6.38 (d, $J = 15.9$ Hz, 1H), 7.20–7.41 (m, 5H); ^{13}C NMR ($CDCl_3$) δ 23.16, 30.00, 49.24, 62.47, 68.29, 100.12, 125.13, 126.51, 127.74, 128.52, 132.89, 136.57. Found: C, 56.77; H, 5.79%. Calcd for $C_{14}H_{17}BrO_2$: C, 56.58; H, 5.77%.

3-Chloro-2-(3-methyl-2-butenyloxy)tetrahydropyran (25d, Mixture of Stereoisomers, 60/40). IR (neat) 2930, 2874, 1734, 1734, 1671, 1438, 1378, 1205, 1132, 1091, 1074, 1013, 950, 873, 730, cm^{-1}; ^1H NMR ($CDCl_3$) δ 1.44–1.57 (m, 1H), 1.69 (s, 3H), 1.76 (s, 3H), 1.78–2.02 (m, 2H), 2.06–2.22 (m, 0.4H), 2.25–2.37 (m, 0.6H), 3.48–3.61 (m, 1H), 3.79–4.02 (m, 2H), 4.07 (dd, $J = 6.9$, 12.0 Hz, 1H), 4.23 (dd, $J = 6.6$, 12.0 Hz, 1H), 4.57 (d, $J = 4.2$ Hz, 0.6H), 4.74 (d, $J = 3.0$ Hz, 0.4H), 5.36 (dd, $J = 6.6$, 6.9 Hz, 0.6H), 5.38 (dd, $J = 6.6$, 6.9 Hz, 0.4H); ^{13}C NMR ($CDCl_3$) For major isomer: δ 17.76, 21.89, 25.59, 28.92, 56.68, 61.89, 64.12, 99.70, 120.15, 137.95. For minor isomer: δ 17.81, 21.89, 25.51, 28.30, 57.08, 59.17, 63.95, 96.61, 120.30, 137.53. Found: C, 58.40; H, 8.10%. Calcd for $C_{10}H_{17}ClO_2$: C, 58.68; H, 8.37%.

3-Bromo-2-(3-phenyl-2-propynyloxy)tetrahydropyran (25e). IR (neat) 2948, 2924, 2852, 1720, 1599, 1490, 1442, 1355, 1204, 1133, 1088, 1071, 1029, 967, 868, 755, 690 cm^{-1}; ^1H NMR ($CDCl_3$) δ 1.45–1.57 (m, 1H), 1.90–2.05 (m, 2H), 2.35–2.46 (m, 1H), 3.63 (ddd, $J = 5.7$, 6.0, 11.7 Hz, 1H), 3.93 (ddd, $J = 3.3$, 8.4, 11.7 Hz, 1H), 4.06 (dt, $J = 3.9$, 5.7 Hz, 1H), 4.52 (d, $J =$ 3.9 Hz, 2H), 4.93 (d, $J = 3.9$ Hz, 1H), 7.29–7.32 (m, 3H), 7.43–7.48 (m, 2H); ^{13}C NMR ($CDCl_3$) δ 22.48, 29.24, 48.63, 55.35, 62.13, 84.16, 86.47, 99.01, 122.47, 128.26, 128.51, 131.79. Found: C, 57.09; H, 5.21%. Calcd for $C_{14}H_{15}BrO_2$: C, 56.97; H, 5.12%.

3-Bromo-2-[1-(3,3-dimethyl-1-butynyl)cyclohexyloxy]tetrahydropyran (25f). IR (neat) 2946, 2930 2850, 1726, 1657, 1600, 1580, 1495, 1356, 1203, 870, 728 cm^{-1}; ^1H NMR ($CDCl_3$) δ 1.25 (s, 9H), 1.43–1.95 (m, 12H), 1.97–2.09 (m, 1H), 2.34–2.45 (m, 1H), 3.58 (ddd, $J = 3.6$, 7.2, 10.8 Hz, 1H), 4.02 (ddd, $J = 3.6$, 7.2, 10.8 Hz, 1H), 4.11 (ddd, $J = 4.8$, 4.8, 7.8 Hz, 1H), 5.21 (d, $J = 4.8$ Hz, 1H); ^{13}C NMR ($CDCl_3$) δ 23.01, 23.08, 25.14, 25.25, 27.20, 30.07, 31.12, 32.57, 38.65, 38.66, 63.25, 75.92, 78.94, 96.18, 98.21. Found: C, 52.14; H, 6.79%. Calcd for $C_{17}H_{27}IO_2$: C, 52.31; H, 6.97%.

7-Phenylmethyl-2,9-dioxabicyclo[4.3.0]nonane (27, Mixture of Diastereomers, 57/43). IR (neat) 3022, 2934, 2866, 1604, 1496, 1454, 1252, 1146, 1100, 1054, 1022, 949, 899, 871, 753, 700 cm^{-1}; ^1H NMR ($CDCl_3$) δ 1.28–1.99 (m, 5H), 2.52–2.88 (m, 3H), 3.34–3.45 (m, 0.43H), 3.60–3.67 (m, 1H), 3.73–3.90 (m, 2.14H), 4.17 (dd, $J = 8.1$, 8.1 Hz, 0.43H), 5.03 (d, $J = 3.6$ Hz, 0.43H), 5.28 (d, $J = 3.6$ Hz, 0.57H), 7.14–7.31 (m, 5H); ^{13}C NMR ($CDCl_3$) For major isomer: δ 19.41, 23.01, 33.27, 38.62, 42.39, 60.87, 69.80, 101.96, 126.20, 128.38, 128.54, 140.20. For minor isomer: δ 20.60, 22.32, 36.52, 39.39, 43.71, 64.21, 73.52, 102.11, 126.24, 128.51, 128.54, 140.14. Found: C, 76.96; H, 8.39%. Calcd for $C_{14}H_{18}O_2$: C, 77.03; H, 8.31%.

Spiro[2,9-dioxabicyclo[4.3.0]nonane-8,1′-cyclohexane] (33). IR (neat) 2924, 2856, 1472, 1450, 1398, 1360, 1219, 1161, 1136, 1092, 997, 962, 914, 876 cm^{-1}; ^1H NMR ($CDCl_3$) δ 1.08 (s, 9H), 1.14–1.92 (m, 14H), 2.79 (ddd, $J = 4.2$, 6.6, 10.5 Hz, 1H), 3.70 (ddd, $J = 1.8$, 3.9, 11.4 Hz, 1H), 3.92 (ddd, $J = 2.4$, 11.4, 11.4 Hz, 1H), 5.08 (s, 1H), 5.18 (d, $J = 4.2$ Hz, 1H); ^{13}C NMR ($CDCl_3$) δ 22.48, 22.55, 23.47, 25.18, 26.80, 30.78, 33.22, 36.40, 37.44, 39.85, 60.59, 81.40, 98.28, 132.15, 145.78. NOE (^1H diffectrum, 300 Hz, $CDCl_3$): irradiation of $\delta =$ 2.75–2.84 (CH) enhancement of signals at $\delta = 1.08$ (CH_3, 0.32%), $\delta = 5.18$ (CH, 2.2%); irradiation of $\delta = 5.08$ (CH) enhancement of signals at $\delta = 1.14$–1.22 (CH_2, 2.3%), $\delta =$ 1.35–1.43 (CH_2, 1.6%).

2-(3-Cyclopropyl-2-butenyloxy)-3-iodotetrahydropyran (3a′). IR (neat) 3078, 2924, 2848, 1659, 1463, 1439, 1382, 1353, 1302, 1202, 1171, 1122, 1021, 942, 866, 814, 694, cm^{-1}; ^1H NMR ($CDCl_3$) δ 0.47–0.68 (m, 4H), 1.41–1.48 (m, 1H), 1.52–1.61 (m, 1H), 1.57 (s, 3H), 1.67–1.81 (m, 1H), 1.92–2.06 (m, 1H), 2.36–2.46 (m, 1H), 3.58 (ddd, $J = 5.1$, 6.3, 8.4 Hz, 1H), 3.95–4.07 (m, 3H), 4.24 (dd, $J = 6.6$, 11.7 Hz, 1H), 4.63 (d, $J = 5.1$ Hz, 1H), 5.42 (dd, $J = 6.6$, 6.9 Hz, 1H); ^{13}C NMR ($CDCl_3$) δ 4.52, 13.95, 18.52, 25.39, 29.42, 32.62, 63.28, 64.26, 101.28, 118.20, 141.83. Found: C, 44.69; H, 6.03%. Calcd for $C_{12}H_{19}IO_2$: C, 44.74; H, 5.94%.

Phenylmethyl-*d*-2,9-dioxabicyclo[4.3.0]nonane (41a, Mixture of Diastereomers, 68/32). IR (neat) 3061, 3026, 2923, 2872, 1736, 1497, 1450, 1250, 1148, 1022, 991, 951, 897, 872, 733, 702 cm^{-1}; ^1H NMR ($CDCl_3$) δ 1.25–2.00 (m, 5H), 2.52–2.88 (m, 2H), 3.41 (dd, $J = 2.7$, 10.4 Hz, 0.32H), 3.59–3.68 (m, 1H), 3.72–3.91 (m, 2.36H), 4.17 (dd, $J = 1.2$, 8.1 Hz, 0.32H), 5.03 (d, $J = 3.3$ Hz, 0.32H), 5.27 (d, $J = 3.9$ Hz, 0.68H), 7.13–7.32 (m, 5H); ^{13}C NMR ($CDCl_3$) For major isomer: δ 19.39, 22.98, 32.90 (t, $J = 19.4$ Hz), 36.47, 42.29, 60.84, 69.75, 101.92, 126.17, 128.48, 128.52, 140.13. For minor isomer: δ 20.56, 22.28, 38.19, (t, $J = 19.1$ Hz), 39.25, 43.65, 64.20, 73.47, 102.08, 126.21, 128.35, 128.52, 139.98. Found: C, 76.38; H + D, 8.56%. Calcd for $C_{14}H_{17}DO_2$: C, 76.68; H + D, 8.73%.

7-(1-Phenyl-3-butenyl)-2,9-dioxabicyclo[4.3.0]nonane (41b, Mixture of Diastereomers, 66/34). IR (neat) 3060, 3024, 2918, 1641, 1604, 1494, 1469, 1454, 1439, 1404, 1278, 1254, 1202, 1149, 1110, 1025, 989, 948, 900, 871, 763, 701 cm^{-1};

^{1}H NMR ($CDCl_3$) δ 1.28–1.68 (m, 4H), 2.16–2.23 (m, 2H), 2.30–2.51 (m, 1H), 2.59–2.78 (m, 2H), 3.36 (dd, $J = 8.1$, 8.1 Hz, 0.34H), 3.50 (dd, $J = 8.1$, 9.9 Hz, 0.34H), 3.57–3.78 (m, 2H), 3.86 (dd, $J = 8.1$, 9.9 Hz, 0.66H), 4.16 (dd, $J = 8.1$, 8.1 Hz, 0.66H), 4.84–4.96 (m, 2H), 5.28 (d, $J = 3.6$ Hz, 0.66H), 5.40 (d, $J = 3.6$ Hz, 0.34H), 5.41–5.60 (m, 1H), 7.08–7.37 (m, 5H); ^{13}C NMR ($CDCl_3$) For major isomer: δ 18.80, 23.01, 35.63, 39.97, 44.45, 45.60, 60.57, 68.75, 101.75, 116.64, 126.51, 127.89, 128.41, 135.64, 143.06. For minor isomer: δ 18.98, 23.17, 35.63, 39.55, 43.92, 46.33, 60.62, 68.69, 101.94, 116.24, 126.69, 127.76, 128.49, 135.88, 142.25. HRMS Found: m/z 258.1628. Calcd for $C_{17}H_{22}O_2$: 258.1620.

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14 In addition, the stereochemical outcome of **2** was also similar to that of EtMgBr-mediated radical reaction: A. Inoue, H. Shinokubo, and K. Oshima, *Org. Lett.*, **2**, 651 (2000).

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17 Recent study on the PhLi-initiated cyclization of olefinic alkyl iodides suggests that β-alkoxy elimination may be the result of rapid expulsion of the allyloxy anion from an electron-rich iodine ate-complex prior to completion of the lithium–iodine exchange reaction. See, W. F. Bailey and M. W. Carson, *J. Org. Chem.*, **63**, 9960 (1998).

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20 Yielding *o*-bromophenol might support the single electron transfer mechanism. A single electron transfer possibly resulted in releasing 2-bromophenoxide anion and the stable allylic radical, whereas iodide and the aryl radical were formed in the case

of **14a**.

21 In general, $Cp_2Zr(H)Cl$ adds to alkenes in CH_2Cl_2 at ambient temperature to provide alkylzirconiums: a) D. W. Hart and J. Schwartz, *J. Am. Chem. Soc.*, **96**, 8115 (1974). b) D. W. Hart, T. F. Blackburn, and J. Schwartz, *J. Am. Chem. Soc.*, **97**, 679 (1975). c) C. A. Bertelo and J. Schwartz, *J. Am. Chem. Soc.*, **98**, 262 (1976). d) J. Schwartz and J. A. Labinger, *Angew. Chem., Int. Ed. Engl.*, **15**, 333 (1976). e) P. C. Wailes and H. Weigold, *J. Organomet. Chem.*, **24**, 405 (1970). f) P. C. Wailes, H. Weigold, and A. P. Bell, *J. Organomet. Chem.*, **27**, 373 (1971).

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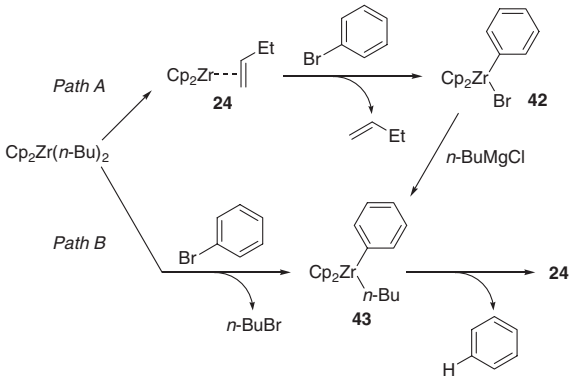
24 It is well documented that THF is a good hydrogen donor to radical species ($K_H = 104\ s^{-1}$): M. Newcomb and D. P. Curran, *Acc. Chem. Res.*, **21**, 206 (1988).

25 Given this pathway, the reactions should proceed with only one equivalent of the zirconocene–olefin complex. However, in this case, two equimolar amounts of $Cp_2Zr(H_2C{=}CHEt)$ are required in order to obtain reasonable yields of the cyclization products.

26 For examples of transmetallation of alkylzirconium to copper, see: a) M. Yoshihuji, M. Loots, and J. Schwartz, *Tetrahedron Lett.*, **15**, 1303 (1977). b) L. M. Venanzi, R. Lehmann, R. Keil, and B. H. Lipshutz, *Tetrahedron Lett.*, **30**, 5857 (1992). c) T. Takahashi, M. Kotora, K. Kasai, and N. Suzuki, *Tetrahedron Lett.*, **32**, 5685 (1994).

27 A solid CuCN was used in this system. When CuCN·2LiCl was employed in this system, the yield was decreased slightly.

28 Takahashi's group also reported an effective method for dehalogenation of aromatic halides with $Cp_2Zr(H_2C{=}CHEt)$. For example, when bromobenzene was treated with 3 equivalent of *n*-BuMgCl and a catalytic amount (10 mol%) of Cp_2ZrCl_2, dehalogenation of bromobenzene proceeded smoothly in high yield. However, they did not propose a mechanism involving a radical intermediate and instead suggested two possible mechanisms (Scheme 15). One involves oxidative addition reaction of aromatic halides to $Cp_2Zr(H_2C{=}CHEt)$ to provide complex **42**. The reaction of **42** with *n*-BuMgCl can afford butyl(phenyl)zirconocene



Scheme 15.

(**43**). β-Hydrogen abstraction from the butyl group provides free benzene and **24** (*Path A*). Another possible mechanism, *Path B* involves metal–halogen exchange reaction. Bromobenzene reacts with dialkylzirconocene to furnish **43** and bromobutane. Furthermore, Takahashi reported that even aromatic chlorides were successfully dechlorinated by alkylmagnesium reagents in the presence of a catalytic amount of Cp_2TiCl_2.[30,31] However, these systems could not be applicable to alkyl halides. This may be due to the formation of an alkylzirconium species followed by β-hydrogen elimination. Thus, our reaction mentioned in this article is complementary to Takahashi's and Schwartz's reactions. a) T. Takahashi, M. Kotora, R. Fischer, Y. Nishihara, and K. Nakajima, *J. Am. Chem. Soc.*, **117**, 11039 (1995). b) T. Takahashi, Y. Nishihara, W.-H. Sun, R. Fischer, and K. Nakajima, *Organometallics*, **16**, 2216 (1997). c) R. Hara, W.-H. Sun, Y. Nishihara, and T. Takahashi, *Chem. Lett.*, **1997**, 1251.

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30 R. Hara, K. Sato, W.-H. Sun, and T. Takahashi, "Abstracts of the 46th Symposium on Organometallic Chemistry," Japan, September 1999, p. 254.

31 Schwartz's group also developed that Cp_2TiCl_2 could catalyze the reduction of aryl halides by sodium borohydride: Y. Liu and J. Schwartz, *Tetrahedron*, **51**, 4471 (1995).